(12) UK Patent Application (19) GB (11) 2 214 382 (13) A

(43) Date of A publication 31.08.1989

(21) Application No 8828573.9

(22) Date of filing 07.12.1988

(30) Priority data
(31) 87729961 (32) 23.12.1987 (33) GB

(51) INT CL⁴
H04N 5/33, G02B 23/12

(52) UK CL (Edition J)
H4F FCC FD18R FD25L FD27L
G2J JB7U

(56) Documents cited
None

(58) Field of search
UK CL (Edition J) G2J JB7U, H4F FCC FCK FDX FJL FJS
INT CL⁴ G02B, H04N
"Derwent WPI (online)"

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(54) **Infra-red image detector systems**

(57) The detection of infra-red image radiation using cheap, high resolution semiconductor array photodetector devices (made of silicon, say) is frequently found to be difficult or impossible because such radiation does not possess sufficient energy to excite electrons in the photodetector material.

A possible solution to this problem involves using the IR radiation to produce, *via* an IR scintillator 23 such as one based on certain refractory metal sulphide materials, radiation of a shorter wavelength that can be absorbed by, and so excite electrons in, these cheap photodetector devices 26. The invention thus proposes an imager sensitve to IR radiation which comprises an IR scintillator (or phosphor) coupled face-to-face eg via fibre optics 25, with a suitable photodetector such that the visible light output generated by the former is received by the latter. The photodetector may be a photoconductive device (eg. a vidicon or CCD camera) or a photoemissive device (eg. an image orthicon or image intensifier, Fig 3).

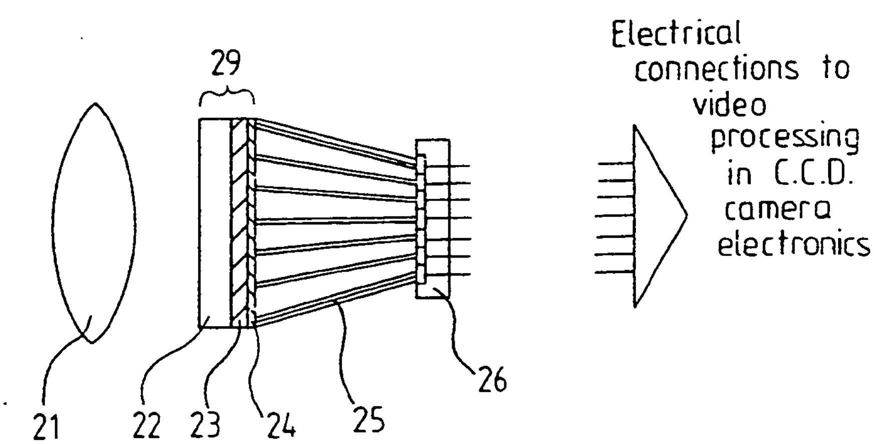

FIG 2

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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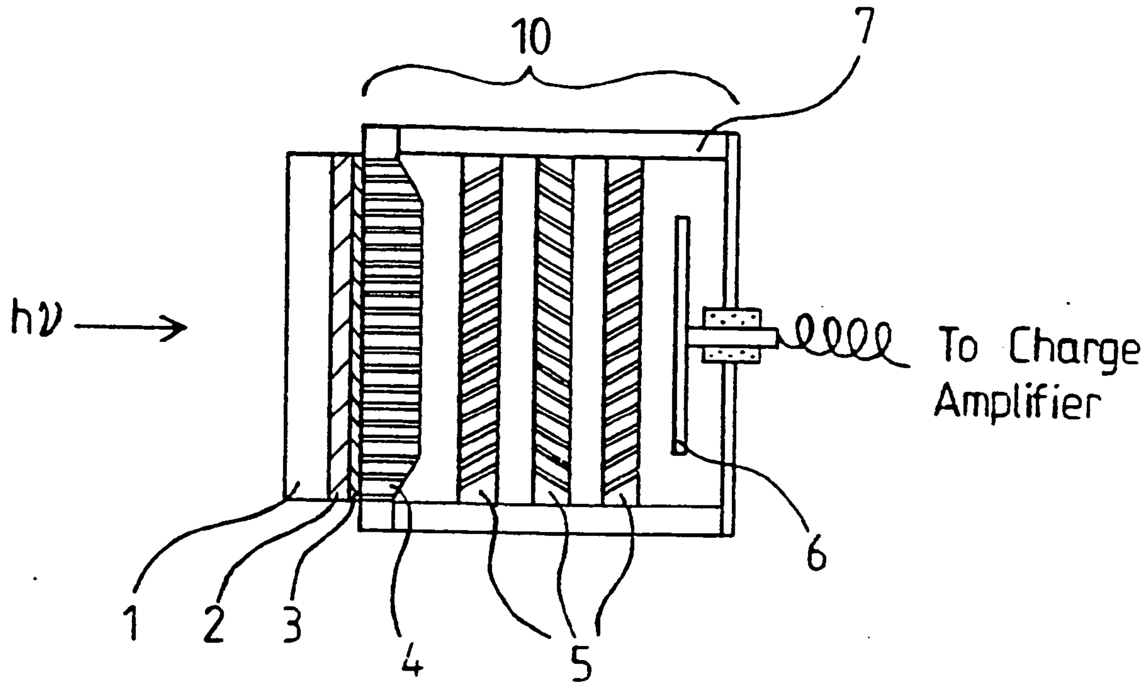

FIG 1

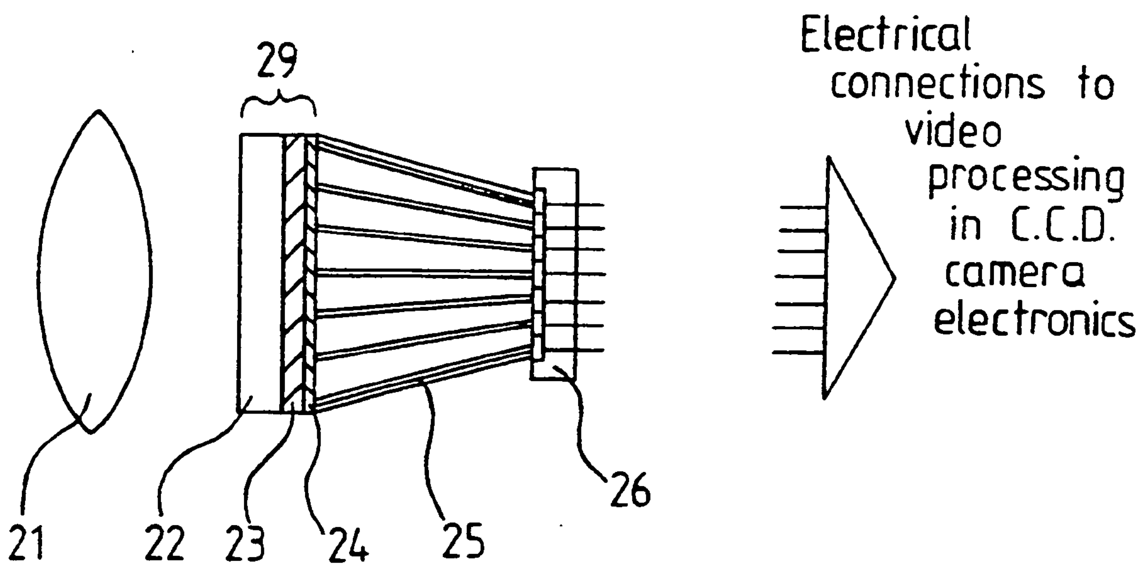

FIG 2

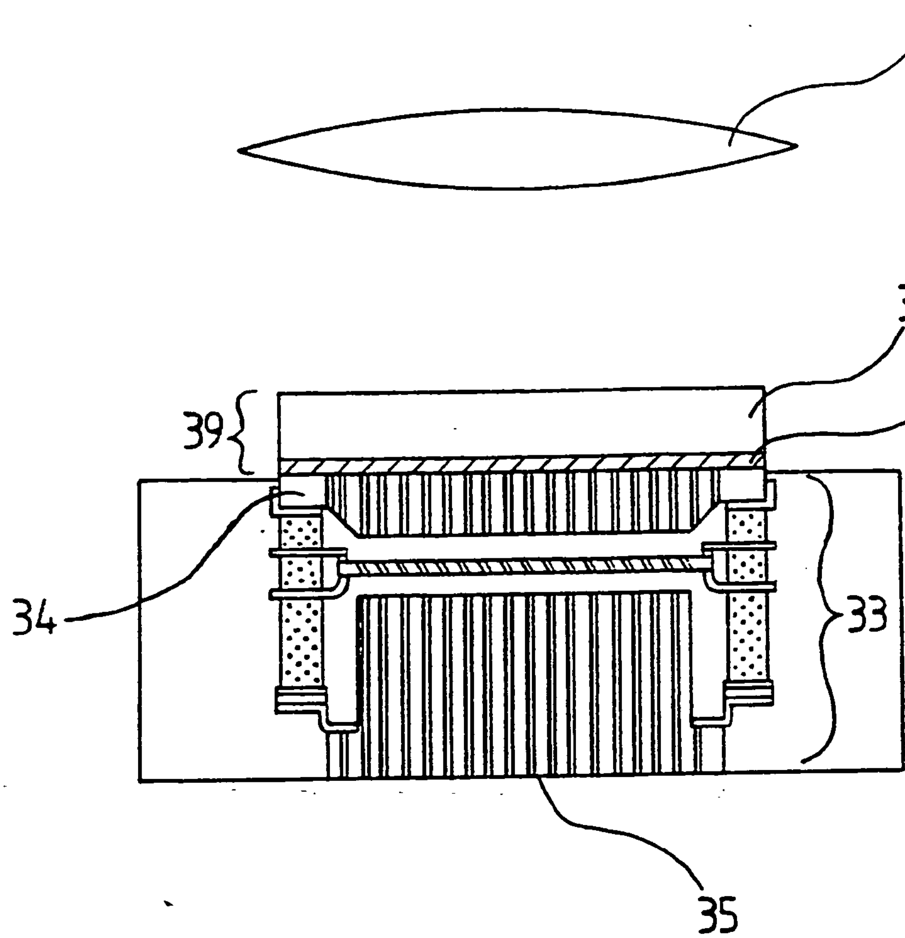

FIG 3

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Image Detector Systems

This invention concerns image detector systems, and relates in particular to such systems that are solid state and both satisfactorily sensitive to infra-red radiation and capable of reasonably high resolution.

Solid state image detector systems may for convenience be divided into two main classes, namely staring arrays, in which the image is formed upon an array (usually two-dimensional) of detector elements - because the image is stationary relative to the array the array is said to "stare" at the image - and mechanically scanned arrays, in which the image is scanned (again, usually in two dimensions) across a single detector element. In a mechanically-scanned system there is only a single detector element, and so it is possible to make that detector from materials which, albeit expensive and difficult to process, have a good wavelength response, being capable of detecting electromagnetic radiation not only in the visible light range but also well into the infra-red (IR). However, the very fact that these systems are mechanically scanned makes them very expensive, with many disadvantages. Staring arrays, on the other hand, as exemplified by various types of charge-coupled device (CCD), are mechanically simple, and thus potentially cheap. Unfortunately, they have only proved commercially feasible in one particular semiconductor material, silicon, which suffers from a poor wavelength response at the "red" end of the spectrum, and generally cannot detect radiation beyond 1.1 micrometre - and

whilst small arrays (with 30×50 elements) of exotic materials such as Indium Antimony (InSb) that do have a reasonable response to red and IR light radiation have been made, these have poor resolution, and are presently extremely difficult - and so expensive - to produce.

Thus, the present situation is that there can easily be obtained a high resolution (300×500 elements) silicon detector system with a response out to the band edge of silicon (1.1 micrometre), but if there is required - as there often is - a solid state imaging detector responsive at longer wavelengths (say, 1.2 micrometre, or more) it has to be either an expensive mechanically-scanned system or a very expensive, low resolution, research device in, say InSb.

The problem, then, in producing a cheap solid state imaging system resides in the photodetectors available, which by and large do not presently enable the provision of cheap, high resolution detector arrays having a good response to the longer wavelengths (especially to IR radiation).

It is possible, though, that a solution to this IR detection problem may be found by approaching the subject from a different direction. Thus, rather than attempting to produce a semiconductor material that is selectively sensitive to IR, "outputting" electrons when irradiated by such light, find instead a material that outputs visible light when illuminated by IR, and couple it to a photodetector (which may be in the form of a cheap, high resolution array) that is acceptably sensitive to that light!

Materials which output light when illuminated by IR are referred to as IR scintillators (or IR phosphors). They are generally insulator materials with a bandgap of 2 to 6 eV, and electron traps somewhere in the midgap

region. The concept of an IR scintillator goes back to the 1940s, when KODAK were interested. However, there has more recently been developed a new class of refractory metal sulphides (particularly strontium sulphide) having this scintillator (or phosphor) effect. These materials (examples of which are sold under the Trade Name QUANTEX by Quantex Inc., of Rockville, Maryland, USA - and available in the UL from AG Electron-Optics Ltd) contain a high density of electron traps in the otherwise forbidden bandgap region, some 2 to 4 eV above the valence band, and electrons can be excited into these traps by exposing the material to blue light. Then, when these materials are subsequently exposed to <u>low</u> energy photons - IR light of wavelength between 0.7 and 1.7 micrometre, which they quite strongly absorb - the illuminating energy can be absorbed by the trapped electrons, giving them sufficient energy to reach the conduction band, from which they can re-combine with a valence band electron, emitting a <u>visible</u> light photon in the process (this explanation, based upon present understanding, may not necessarily be correct, though it seems satisfactorily to explain the observed phenomena). The visible light output is in the orange region of the spectrum - around 0.6 micrometre.

The invention proposes that these refractory metal sulphides should be used in conjunction with and ahead of - possibly as a semi-transparent coating on - a visible light photodetector system. The combination would then have the desired sensitivity to IR together with the conventional photodetector's normal potentially low cost, ease of manufacture, and high resolution.

In one aspect, therefore, this invention provides an infra-red sensitive image detector device comprising the combination of an infra-red scintillator and a suitable photodetector, the latter being arranged so as to receive the visible light output of the former.

The IR scintillator component is conveniently an appropriately-supported layer of one of the refractory metal sulphides mentioned hereinbefore. That material known as QUANTEX Q-31 has an input sensitivity peaking at about 1.2 micrometre, whilst that known as QUANTEX Q-42 peaks nearer to 1.0 micrometre (Q-42 appears to be formed from strontium sulphide; it was briefly described in "Physical Review", Vol 108 (1957), pp 663 et seq., and may be doped with Ce, Sm and/or Eu to enhance the IR response). However, other materials are used to make IR-scintillators, such as the more recent YF_3 with Er and Yb doping, $BaEr_2$ and PbF_2/GeO_2 (described in "Appl. Phys. Letts., 39, pp587-589, 1981).

The resolution of phosphor powders is a function of the particle size. Optical absorption is also clearly a function of layer thickness, and of wavelength. Considerations of absorption and resolution are almost certainly in conflict for the type of device here contemplated. Since the normal size of a minimum resolvable element in modern image intensifiers is around 20 micrometre, this figure sets an absolute upper limit to the desirable thickness of the IR conversion phosphor. Thus, allowing for the resolution degradation in the other components in the detection system, a desirable layer thickness for the IR scintillator would be in the region of 5 micrometre, and such a layer can easily be sprayed or brushed, or settled by aqueous sedimentation, onto a suitable support (a fibre optic

faceplate, for example - see below) using a binding agent such as an acryllic lacquer.

Present work shows that the efficiency of these scintillators is dependent upon the purity and crystallinity of the material. For example, sputtered layers which are annealed at high temperature (around 450°C) after deposition are some two to three times more efficient than those produced by sedimentation from a powder by aqueous sedimentation. Moreover, for the efficiency of the scintillator layer to be the highest the supporting substrate upon which it is mounted is also found to be important. The best layers are formed not directly onto the photodetector (see below) but onto an intermediate sapphire layer. Scintillators sputtered onto sapphire, and re-crystallised by annealing, can then be bonded (by optical cement) to the photodetector.

Photodetectors - that is, devices that output an electrical signal indicative of the amount of light falling on them (by "light" is meant photons; electromagnetic radiation falling within the relatively narrow energy band from infra-red though visible to ultra violet) - are now common in a number of fields. The modern varieties are mostly semiconductor devices, and they may generally be divided into two major types: the photoemitters, which output electrons in response to the radiation illuminating them, and the photoconductors, which change their electrical resistance when illuminated.

Photodetectors are not usually employed by themselves, but are instead associated with other apparatus that can accept and manipulate their output to provide some useful result. For example, in the case of photoemissive devices, the absorption of the illuminating photons by the photodetective layer is

followed by electron emission from the layer (into vacuum), and this is then often followed by electron multiplication in the subsequent apparatus before the original "optical" signal is reconstituted either electronically (in the case of a photomultiplier or image orthicon) or optically by means of a phosphor screen (in the case of an image intensifier). Similarly, in the case of photoconductive devices, a p-n junction behind the photoactive layer is often used to separate out the resistance-altering photoelectrons, and again the image or signal is re-processed by electronic means (perhaps involving a scanning electron beam, as in the case of a vidicon, or an amplifier, as in the case of a CCD or photodiode).

In the present invention the photodetector component may be either a photoconductive element or a photoemissive element. A typical photoemissive element would be a layer of a semiconductor material such as Na_2KSb/Cs (known as S-20 or S-25), which is sensitive to visible light radiation, and can be processed to give a quantum efficiency of 20% or so for the orange light emitted by a typical scintillator component. Another typical photodetector is a silicon array, of the CCD variety, as used in many modern television cameras.

Generally, the scintillator and photodetector will be arranged in face-to-face contact, the detector receiving light that has, in effect, passed through the scintillator. Where appropriate, the scintillator component may be present as a layer placed directly on the light-input surface of the photodetector component (as mentioned hereinbefore). It may, however, be desirable to apply the scintillator component first to a fibre optic plate (or even a plain glass plate), and then, using optical cement, to bond the thus-mounted

scintillator to any of a whole range of standard photodetector systems - image intensifiers, high speed camera tubes, low light television cameras, photomultipliers, etc. Where, for example, the scintillator component is applied to a fibre-optic faceplate, possibly coupled in its turn (using optical cement) to an imaging device such as an image intensifier or CCD, it may prove attractive partially to remove the cores of the fibre-optic fibres by chemical etching to a depth of 5 micrometre or so. The grains of the scintillator component material can then be separated either mechanically or optically (as disclosed in US Patent 4,654,558 in connection with phosphors).

In use, the scintillator component of the device is exposed to strong "blue" light (it is readily charged and re-charged by exposing it to daylight, or to a normal fluorescent tube lamp, for a few seconds). The trapped electrons are sufficiently stable that the device may then be stored in the dark for a period as long as several weeks, during which time only a few of the trapped electrons will leak away, thus leading to only a small loss of efficiency.

The density of electron traps in the scintillator component is such that the device can be used for many hundreds of hours at the sort of very low photon illumination levels that would require the employment of an image intensifier, photomultiplier, etc., though if exposed to high intensity infra red the useful life on one charge is measured in seconds only.

As intimated hereinbefore, the whole device may, of course, be associated with means for manipulating the

photodetector component's electron output. For example, a photoemissive photodetector component may be associated with means for amplifying the output electrons and for rendering the resultant amplified output visible - typically (as in a second or third generation image intensifier) a microchannel plate the output electrons from which fall upon a phosphor screen where they are converted back into visible light.

Typical quantum efficiencies for an IR scintillator of the refractory metal sulphide variety are in the range 1 to 10% for the wavelength range 1.5 to 1.2 micrometre, with a reasonable response as far out as 1.7 micrometre, and even when this is factored by the average 60% conversion efficiency of visible light to electrons for a typical silicon CCD, or - and worse - the average 20% efficiency of a typical photocathode, it is still possible to achieve overall quantum yields of 0.2 to 2%, and possibly up to 6%, in the above wavelength range. In general, available IR photocathodes have a conversion efficiency of less than 0.1% at 1.1 micrometre, and several orders of magnitude less at 1.3 micrometre (although some of the more exotic and expensive semiconductor devices - using InSb, for instance - have quantum efficiencies as high as 50%).

Basically, the imagers of the invention - those coupling an IR-scintillator to a conventional visible-light sensitive silicon array - enjoy the advantages of spectral coverage out to 1.7 micrometre at low cost and with the high resolution available in silicon. The low cost, and tractability, of silicon as compared with the primitive processing technology of the more exotic IR-sensitive materials surely compensates for the lower quantum efficiency.

Although the image detector systems of the invention may make use of photodetector systems that are sensitive to visible light, and themselves need no cooling (unlike those sensitive to infra-red) to reduce thermally-generated noise, nevertheless <u>any</u> IR-sensitive device will suffer from thermal dark noise, and IR scintillators are unfortunately no exception. Thus, though it is not generally visually apparent, all IR scintillators glow in the dark as a result of thermal excitation, albeit at a low level. Coupling them to an image intensifier, photomultiplier or CCD, however, makes this glow all too evident. To get the best results, then, it is necessary to cool them - and in this respect they do not appear to differ greatly from previous IR detectors - viz, at 1 micrometre the dark current noise output (or, rather, the minimum detectable power) is about 1 microwatt at 20°C (300°K). To reduce this noise output, and so the detectable power minimum, requires cooling, and in practice a drop of 20°C results in a drop in noise by a factor of 10 for each 20°C at around 1 micrometre. Thus, for the IR scintillator used in the invention it is anticipated that it will often be necessary to reduce the temperature to -20°C to get down to nanowatt detection levels. For ultimate photon counting performance, the operating temperature is likely to be much colder.

Various embodiments of equipment using an IR-scintillator coupled to a photodetector of some sort are shown, though by way of illustration only, in the accompanying Drawings in which:

<u>Figure 1</u> is a diagrammatical sectional view through an infra-red photon counting device;

<u>Figure 2</u> is a diagrammatical sectional view through an infra-red television camera; and

<u>Figure 3</u> is a diagrammatical sectional view through an infra-red image intensifier.

The infra-red photon counter of Figure 1, useful perhaps in infra-red astronomy, comprises a substrate (1) carrying an IR-scintillator layer (2). The whole is glued, scintillator layer down, by optical cement (3) to the fibre optic input window (4) of a photomultiplier (10) itself comprising the window 4 and a cascade of micro-channel plates (as 5) the electron output of which impinges upon anode (6), all bonded to a vacuum envelope (7).

The infra-red television camera of Figure 2 (only the "optical" front end is shown in the Figure) has an image-forming lens (21) through which infra-red light is

focussed onto an IR-scintillator (29) comprising a scintillator layer (23) on a suitable substrate (22). The scintillator 23 is glued face down by a layer of optical cement (24) to a fibre optic image size corrector (25) providing optical coupling to a silicon charge coupled device (CCD: 26). The output of this CCD is fed to the required video processing electronics (not shown).

Figure 3 shows an infra-red image intensifier. It comprises a lens (38) feeding IR light to an IR-scintillator (39), with a scintillator layer (32) on a sapphire substrate (31), mounted on the fibre optic input window (34) of the housing of an image intensifier (33). The output from the intensifier is fed out <u>via</u> a fibre optic window (35) for displaying an intensified (visible) image of the original IR image.

CLAIMS

1. An infra-red (IR) sensitive image detector device comprising the combination of an infra-red scintillator and a suitable photodetector, the latter being arranged so as to receive the visible light output of the former.

2. An image detector as claimed in Claim 1, wherein the IR scintillator component is made of one of those materials known as QUANTEX Q-31 and QUANTEX Q-42 and believed to be essentially strontium sulphide.

3. An image detector as claimed in Claim 2, wherein the IR scintillator material is in the form of a layer having a thickness in the region of 5 micrometre.

4. An image detector as claimed in either of Claims 2 and 3, wherein the IR scintillator material is sputtered into place on a suitable substrate, and thereafter annealed.

5 An image detector as claimed in Claim 4, wherein the supporting substrate upon which the IR scintillator material layer is mounted is an intermediate sapphire layer.

6. An image detector as claimed in any of the preceding Claims, wherein the photodetector component is in the form of a silicon array.

7. An image detector as claimed in any of the preceding Claims, wherein the IR scintillator component is mounted on a fibre optic plate itself bonded to the photodetector component.

8 An image detector as claimed in any of the preceding Claims, wherein the combination of IR scintillator and photodetector is associated with means for cooling the scintillator.

9. An image detector as claimed in any of the preceding Claims, wherein the combination of IR scintillator and photodetector is associated with means for manipulating the photodetector's output.

10. An infra-red sensitive image detector device as claimed in any of the preceding Claims and substantially as hereinbefore described.

11. An image intensifier, photomultiplier or television camera, whenever employing an image detector as claimed in any of the preceding Claims.

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